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ACCURACY OF DETERMINATION OF THE DIELECTRIC CONSTANT AND THE TEMPERATURE OF A SUBSURFACE LAYER FROM POLARIZATION MEASUREMENTS

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16. Abstract The mathematical relationship is analyzed between brightness temperatures expressed in two orthogonal polarizations of martian thermal radiation, which were measured by the radiometer of the Mars-3 planetary probe (LC/FRD S&T Alert No. 1659), and properties of martian soil (dielectric constant ε and T containing the instrumentation parameters are utilized to evaluate the influence of particular errors on the relative error of the ε and T determination. The influence of the radiometer parameters, errors in determining the antenna orientation, and errors of the telemetering system on the total error in ε and T determination, are evaluated. The zones are calculated for optimum angles of radiometer antenna orientation with respect to the surface at which the minimum error is ensured. Calculations are also made for the maximum possible error caused by depolarization of radiation received by the nearest side lobes of the antenna. It is shown that, with the existing instrumentation and the optimum choice of experimental conditions, error in the determination of ε can be reduced to 10-15%.

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SUMMARY

Errors in measurement of the dielectric permeability ε and temperature of the subsurface layer T by polarization measurements of Mars radio emissions by the Mars-3 planetary probe are analyzed. The effect of the internal parameters of the onboard radiotelescope, errors in determination of antenna orientation and errors of the telemetering system on the total error in determination of ε and T are evaluated. The zones of the optimum angles of radiometer antenna orientation with respect to the surface, at which the minimum error in determination of ε is insured, are calculated. The maximum possible errors in determination of ε, caused by depolarization of radiation received by the nearest side lobes, are calculated.

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N. N. Krupenio, V. A. Ladygin and N. Ya. Shapirovskaya

This work is devoted to problems of accuracy in determination /740* of the dielectric permeability ε and the temperature T of a sub-surface layer of the planet, from measurements of the intensity and polarization of the thermal radiation, by the radiometer installed aboard the planetary probe.

The radiometer measures the half-sum (total channel) and difference (difference channel) of the brightness temperatures of the surface, in two orthogonal polarizations. This instrument was installed aboard the Mars-3 planetary probe [1].

1. Accuracy of Polarization Measurement in Mars-3 Planetary Probe Onboard Experiment

The experimental procedure and method of processing its results has been described in works [1-3]. It was shown in work [3] that the brightness temperatures in two orthogonal polarizations ($T_{b\perp}$, the vertical polarization, and $P_{b\parallel}$, the horizontal polarization) are determined from the output voltages of the telemetering system, by means of the following expression:

$$T_{b\perp} = \frac{2\eta T_{in} - T_{ex}(\eta - 1)}{2\eta(1 - \beta + \beta_{s1})(U_{h\kappa} - U_{\kappa\Sigma})}\left[(U_{\Sigma} - U_{\kappa\Sigma}) + \frac{(U_{-} - U_{\kappa-})K_{\Sigma}}{2K_{-}}\right], \quad (1)$$

$$T_{b\parallel} = \frac{2\eta T_{in} - T_{ex}(\eta - 1)}{2(1 - \beta + \beta_{s1})(U_{h\kappa} - U_{\kappa\Sigma})}\left[(U_{\Sigma} - U_{\kappa\Sigma}) - \frac{(U_{-} - U_{\kappa-})K_{\Sigma}}{2K_{-}}\right], \quad (2)$$

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* Numbers in the margin indicate pagination in the foreign text.

where η is the ratio of the efficiencies of the vertical and horizontal polarization channels; T_{in} and T_{ex} are the temperatures inside and outside the pressurized instrument container, respectively; β is the scattering coefficient of the antenna in the zones outside the main lobe; β_{sl} is the scattering coefficient of the antenna in the zones of the nearest side lobes; K_{Σ}/K_{-} is the ratio of the gains of the total (Σ) and difference ("--") channels. The voltage on the telemetering system outputs: $U_{\Sigma}(U_{-})$ is the voltage corresponding to the measured noise temperatures in the total (difference) channel; $U_{K\Sigma}(U_{K-})$ is the voltage, corresponding to the measurement of the noise temperature of space by the total (difference) channel; U_{hK} is the voltage, corresponding to connecting the matched load to the total channel (hot calibration voltage). /741

The connection of the brightness temperatures in two orthogonal polarizations to the surface characteristics ε and T is based on the polarization measurement method considered for the moon in works [4-6]. We selected a model of the surface layer of Mars for the calculations, which was uniform in electrical properties, smooth and having small electrical losses at the wavelength measured. In this case, the brightness temperatures of the surface, for the vertical and horizontal polarizations, are determined in the following manner:

$$T_{bv}=T(1-\rho_v), \quad (3a)$$
$$T_{bh}=T(1-\rho_h). \quad (3b)$$

T_{bv} lies in the plane of incidence (the plane of incidence passes through the axis of the antenna directional pattern and normal to the surface at the point of observation), and T_{bh} in the orthogonal plane, which also passes through the axis of the directional diagram. The connection of T_{bv} and T_{bh} to the brightness temperatures received by the antenna ($T_{b\perp}$ and $T_{b\parallel}$) is written [4]: /742

$$T_{b\perp}=T_{bv}\cos^2\gamma+T_{bh}\sin^2\gamma, \tag{4a}$$

$$T_{b\parallel}=T_{bh}\sin^2\gamma+T_{bv}\cos^2\gamma, \tag{4b}$$

where γ is the angle of inclination (the angle of rotation of the plane of the vertical polarization of the antenna relative to the plane of incidence), ρ_v and ρ_h are the Fresnel power reflection coefficients. As is well known, ρ_v and ρ_h are functions of ε and of the angle of incidence θ (the angle between the axis of the antenna directional diagram and the normal to the surface).

Using expessions (3) and (4) and the Fresnel formula for the reflection coefficient, we find the roots of equations (1) and (2). A nontrivial solution of equations (1) and (2) will be:

$$\varepsilon=\frac{\sin^2\theta}{\sin^2(\theta-z)} \tag{5}$$

$$T=\frac{2\eta T_{in}-T_{ex}(\eta-1)\sin^2(2\theta-z)}{(1-\beta+\beta_{gl})(U_{h\kappa}-U_{\kappa\Sigma})\sin 2\theta\sin(2\theta-2z)}\times$$
$$\times\frac{\eta(1+\cos 2\gamma)\left[(U_\Sigma-U_{\kappa\Sigma})-\dfrac{U_--U_{\kappa-}}{K}\right]-(1-\cos 2\gamma)\left[(U_\Sigma-U_{\kappa\Sigma})+\dfrac{U_--U_{\kappa-}}{K}\right]}{4\eta\cos 2\gamma}, \tag{6}$$

where $K=\dfrac{2K_-}{K_\Sigma}z$ is a parameter, which can be expressed through the brightness temperatures of the instrument, in the form:

$$\cos^2 z=\frac{\cos^2\gamma T_{bh}-\sin^2\gamma T_{bv}}{\cos^2\gamma T_{bv}-\sin^2\gamma T_{bh}}, \tag{7a}$$

$$\cos^2 z = \frac{\eta(1+\cos 2\gamma)\left[(U_\Sigma - U_{K\Sigma}) - \frac{U_- - U_{K-}}{K}\right] - (1-\cos 2\gamma)\left[(U_\Sigma - U_{K\Sigma}) + \frac{U_- - U_{K-}}{K}\right]}{\eta(1-\cos 2\gamma)\left[(U_\Sigma - U_{K\Sigma}) - \frac{U_- - U_{K-}}{K}\right] + (1+\cos 2\gamma)\left[(U_\Sigma - U_{K\Sigma}) + \frac{U_- - U_{K-}}{K}\right]} \quad (7b)$$ /743

The resulting dependence (5) and (6) of ε and T on all the parameters permits calculation of the effect of individual errors on the relative error in determination of ε and T.

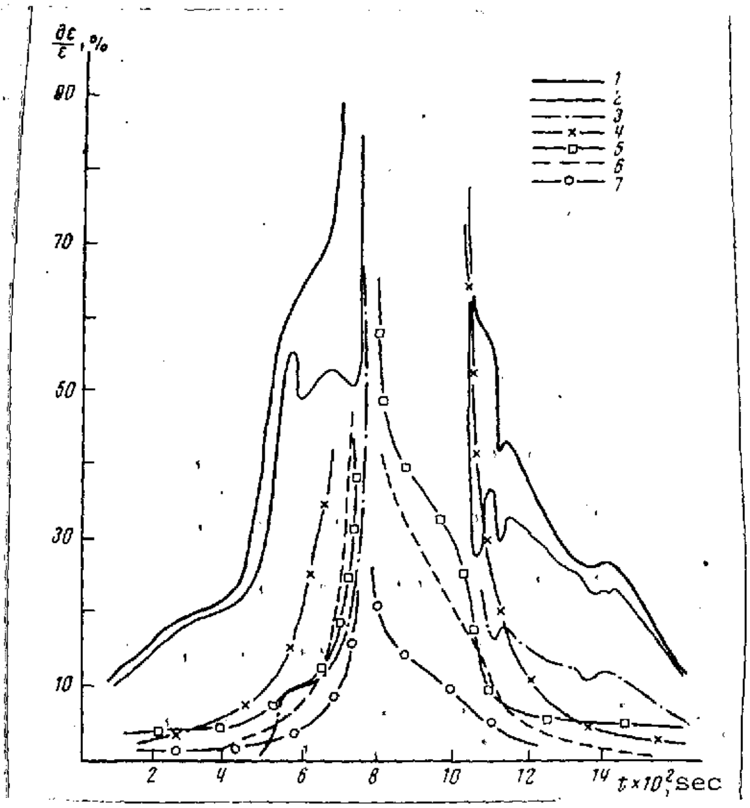

Fig. 1 Errors in determination of ε in 1 Mars-3 planetary probe session: 1) total error, 2) error from $\delta\Theta$; 3) from $\delta\gamma$; 4) from $\delta\eta$; 5) from δK; 6) from U_-; 7) from U

On the assumption that the errors in the apparatus and measurement system parameters $\delta\Theta$, $\delta\gamma$, $\delta\eta$, δK, δU_Σ, δU_-, $\delta U_{K\Sigma}$, δU_K, δU_{HK}, δT_{in}, δT_{ex}, $\delta(\beta, \beta_{bb})$ are mutually independent and have a normal distribution, we calculated the relative errors in determination of ε and T, caused by the error of one of the parameters, $\delta\phi_i$ (in this case, the remaining parameters were "frozen"). The results of these calculations, for one of the measurement sessions carried out by the Mars-3 planetary probe (of 27 December 1972) are presented in Figs. 1 and 2. The relative measurement time is plotted on the abscissa. Each moment of the measurement corresponds to its angle Θ and γ (Fig. 3). The following error values were used in the calculations: $\delta\Theta = \delta\gamma \leq 3°$, estimates obtained from results of trajectory measurements; $\delta\eta/\eta = 0.4\%$, obtained from experiment [3]; $\delta K/K = 5\%$, obtained from preflight ground measurements;

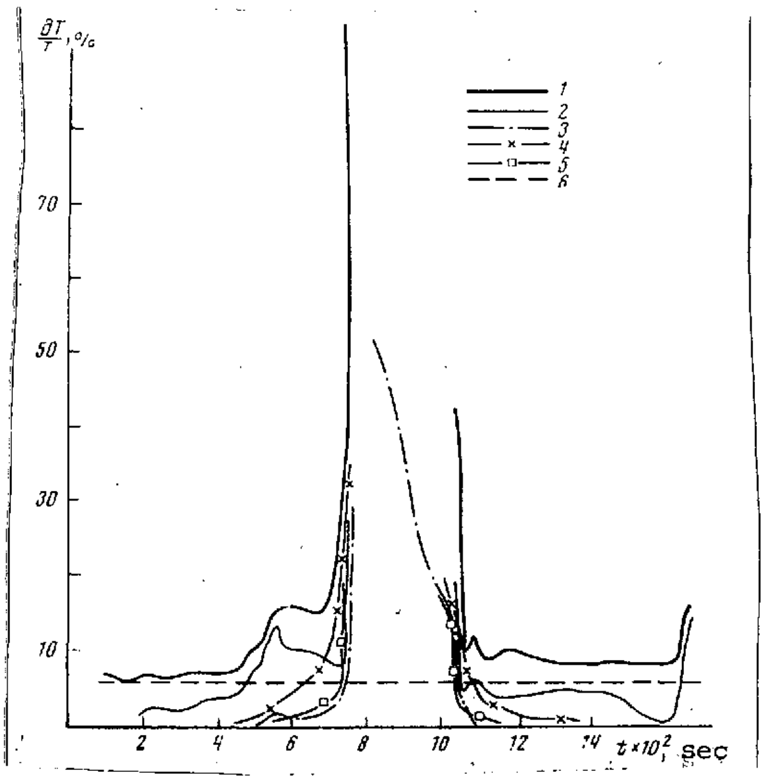

Fig. 2 Error in determination of T in 1 Mars-3 planetary probe session:

1) total error; 2) error from $\delta\theta$; 3) from $\delta\gamma$; 4) from $\gamma\eta$; 5) δK; 6) from $\delta\beta$.

$\delta U_{\Sigma} = \delta U_{-} = \delta U_{hK} = 0.5E$; $\delta U_{K-} = 0.7E$, $\delta U_{K\Sigma} = E$, obtained experimentally, where E is the value of the quantum level of the telemetering system voltage, $\delta T_{in} = \delta T_{ex} = 1.3°$ K, obtained from the experiment.

At angles $\theta = 0°$ and $\gamma = 45$ and $135°$ (we call them critical), determination of ε and T by measurement of the brightness temperatures in two orthogonal polarizations is theoretically impossible (see (5) and (6)). Close to the critical angles, the errors in determination of ε and T increase sharply. In this case, all the components determining the errors in ε and T increase. In sections more than ±20° from the critical angles, the errors in determination of ε are less than 30% and of T, less than 10%. In these regions, the errors are basically determined by inaccuracy in determination of angles θ and γ in orbit.

In the experiment, $\delta\theta = \delta\gamma \leq 3°$, and this error arises mainly, owing to poor determination, at the moment of intersection of the

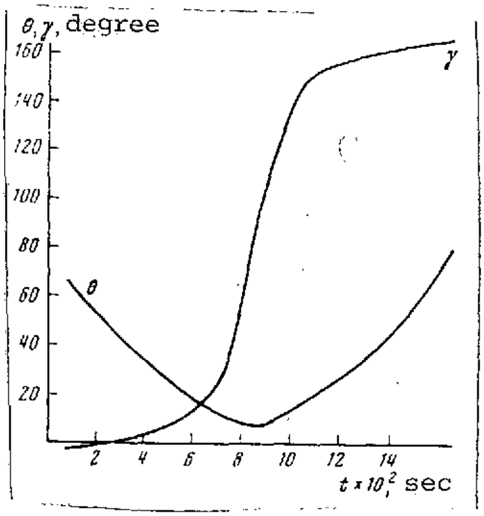

Fig. 3 Change in angles θ and γ in 1 Mars-3 planetary probe session.

axis of the antenna directional pattern and the limb of the planet. If the error in determination of the angles could be successfully reduced to $\delta\Theta = \delta\gamma = 1°$, at angles more than ±20° from the critical angles, the accuracy in determination of ε would be no poorer than 12-15%, all else being equal.

The amount of error of the ratio of the efficiencies of the vertical and horizontal radiometer channel circuits (η) is of great importance for accuracy in determination of ε and T. Through determination of η experimentally, the error δη is successfully reduced considerably (by more than an order of magnitude), compared with determination of η from preflight ground measurements and, thus, $\frac{\partial\varepsilon}{\partial\eta}\delta\eta$ is reduced to a value of ≤ 8%, at angles more than ±20° from the critical angle.

Next in importance is the error in determination of the ratios of the gains of the total and difference channels, K. In the Mars-3 planetary probe experiment, δK = 5%, since the value of K was taken from preflight ground measurements. At angles more than ±20° from the critical angles, the value of $\frac{\partial\varepsilon}{\partial K}\delta K \leq 5\%$. In this case, if the error due to inaccurate determination of angles Θ and γ can be reduced, it is reasonable to incorporate a supplementary calibration into the radiometer, permitting determination of K directly from the experiment. /744

In the experiment carried out, the error due to quantization of the levels in the telemetering system shows considerably less error, which was discussed above.

In that flight geometry, in which the connection of the antenna and brightness temperatures can be reflected by the equations

$$\begin{vmatrix} T_{A\perp}=T_{b\perp}(1-\beta+\beta_{bb}), \\ T_{A\parallel}=T_{b\parallel}(1-\beta+\beta_{bb}), \end{vmatrix} \qquad \begin{matrix} (8a) \\ (8b) \end{matrix}$$

the accuracy in determination of the scattering coefficients in the main and side lobes, does not play a part in calculation of the error in ε, but it is significant for errors in T. At $\delta(1 - \beta + \beta_{bb}) = 5\%$, the error in determination of T is approximately 5.5%, at all values of angles θ and γ, i.e., at angles more than $\pm 20°$ from the critical angles, it is not decisive. This /745
error can be reduced, by means of more careful antenna measurements, carried out directly aboard the planetary probe.

Errors in T, due to error in determination of T_{in} in the experiment $\leq 0.5\%$, and owing to $T_{ex} \leq 0.01\%$.

If the dielectric permeability ε is determined for one specific point on the surface of the planet, at which measurements of the radio brightness temperatures in two orthogonal polarizations were carried out (for example, by ground radar measurements), the errors in $\partial\varepsilon/\varepsilon$ and $\partial T/T$ relative to this reference point can be calculated, as functions of independent errors of the angles and the measurement system. As the calculations show, these errors turn out to be approximately one-fifth those in determination of ε and T by internal standards.

2. Effect of Radiometer Antenna Orientation on Accuracy in Determination of ε from Polarization Measurements

Since accuracy in determination of ε by the polarization method depends extremely critically on the values of angles θ and γ, it is of interest to develop the dependence of $\delta\varepsilon/\varepsilon$ on angles θ and γ, for an ideal instrument (the errors in the parameters of which and in the measurement system equal zero), and to determine the optimum angles θ_{opt} and γ_{opt}, at which the accuracy in determination of ε is at a maximum.

Using equations (5) and (7a) and considering the errors in trajectory measurements of angles θ and γ and the instrument and measurement system parameters to be independent, we obtain:

$$\frac{\delta\varepsilon}{\varepsilon}=\left\{\left[\frac{1+\cos 2\theta}{\sin 2\theta}-\sqrt{\frac{2\varepsilon}{1-\cos 2\theta}-1}\right]^2\delta\theta^2+\right.$$
$$+\left[\sqrt{\frac{2\varepsilon}{1-\cos 2\theta}-1}\times\frac{\sin 2z}{1-\cos 2z}\times\frac{1+\frac{1+\cos 2z}{2}}{\cos 2\gamma}\right]^2\delta\gamma^2+ \tag{9}$$
$$\left.+\left[\sqrt{\frac{2\varepsilon}{1-\cos\theta}-1}\times\frac{1+\frac{1+\cos 2z}{2}}{\sin 2z\cos 2\gamma}\right]\delta S^2\right\}^{1/2},$$

where

$$\cos z=\frac{\sin^2\theta}{\sqrt{\varepsilon}}+\cos\theta\sqrt{1-\frac{\sin^2\theta}{\varepsilon}}$$

$$S=\frac{T_{b\perp}-T_{b\parallel}}{T_{b\perp}+T_{b\parallel}},$$

$T_{b\perp}$ and $T_{b||}$ are expressed only through the instrument parameters (equations (1) and (2)). For an ideal instrument (considering δ $\delta S = 0$), the dependence of $\delta\varepsilon/\varepsilon$ on Θ and γ, for various values of ε, from 1.5 to 6.5, were calculated. Here, errors $\delta\Theta$ and $\delta\gamma$ were assumed to be 0.5°. A curve of $\partial\varepsilon/\varepsilon = f(\Theta)$ was plotted from the calculation results, for various γ and Θ (see Fig. 4).

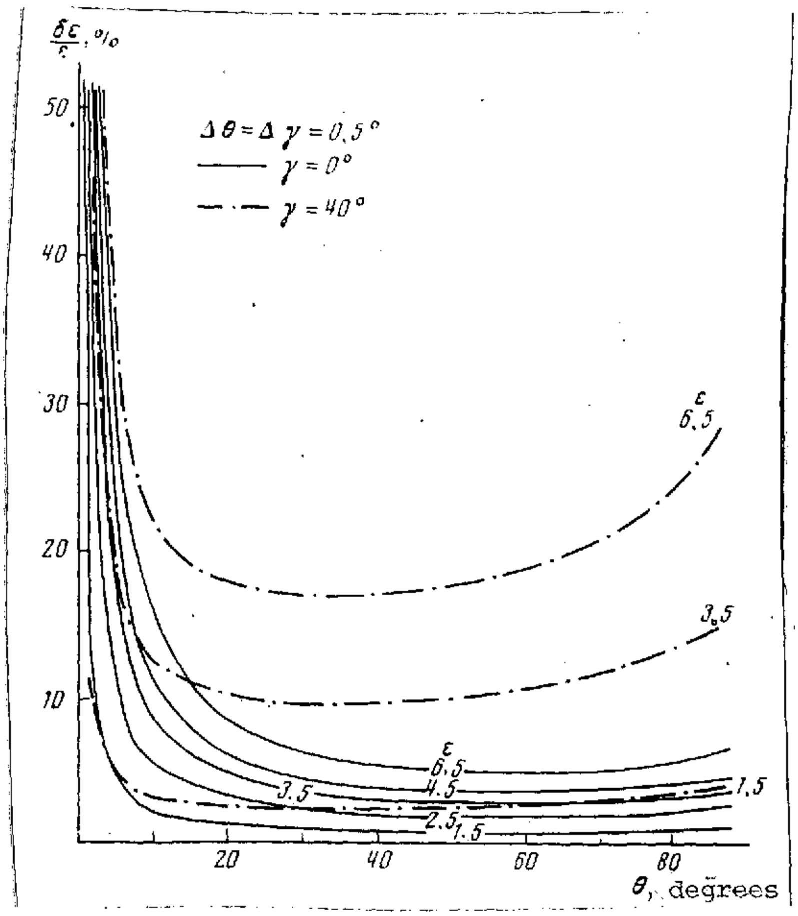

Fig. 4 Accuracy in determination of ε vs. angles Θ and γ

As is evident from Fig. 4, the value of the optimum angle Θ is in the 50° region, is practically independent of the value of ε and it changes somewhat in measurements of γ. The zone around Θ_{opt}, within which $\partial\varepsilon/\varepsilon_{opt} \leq \pm 5\%$, is quite large (from 8 to 80%, on the average), and it decreases with increase in measured parameter ε and with change in angle γ. At angles γ close to 45°, the error $\partial\varepsilon/\varepsilon$ increases/746 considerably, at the same ε and angle Θ (approximately 3 times for $\gamma = 40°$ over $\gamma = 0°$).

The results of the calculations presented in Fig. 4 may serve as a criterion for selection of the optimum location of the polarization radiometer antenna, in measurement of the characteristics of the underlying surface from an aircraft and from a satellite, which is oriented along the gravitational or infrared verticals. Such operating procedures are most advisable for solution of problems connected with study of earth resources from space.

3. Error in Determination of ε Owing to Depolarization of Radiation in the Nearest Side Lobes

In all the calculations of accuracy of measurement described above, it was considered that 100% of the radiation received by the nearest side lobes was polarized and, consequently, the brightness temperature received by the main lobe ($T_{b\perp}$ or $T_{b\parallel}$) equals the brightness temperature in the nearest side lobes.

As a matter of fact, of course, 100% of the radiation in the nearest side lobes is not polarized. To estimate the maximum error, which is caused by designation of T_{bsl} and by equating $T_{bsl} = T_{b\perp}$ or $T_{b\parallel}$, we will consider that the radiation in the nearest side lobes is completely unpolarized and equal to the background brightness temperature T_{bb}. If a planet is being investigated, for which T_{bb} is unknown and in which there may be large, abrupt temperature drops also, within the width of the antenna directional pattern, for example, Mars, it can be considered, with a sufficient degree of accuracy:

$$T_{bsl} = \frac{T_{b\perp} + T_{b\parallel}}{2} \tag{10}$$

for each moment of measurement.

Using formulas (5), (7a), (8) and (10) and assigning ε from 1.5 to 6.5, varying angle Θ, we calculate the maximum value of the relative measurement error Δ, owing to depolarization of the radiation in the nearest side lobes.

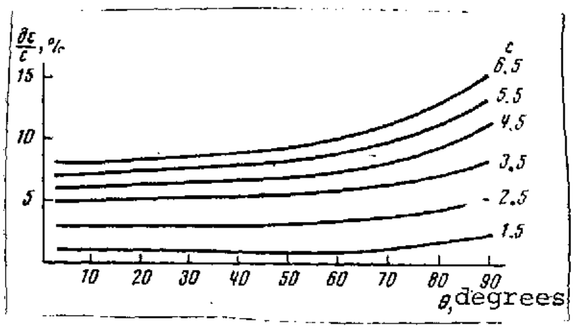

Fig. 5 Maximum error in determination of ε, owing to depolarization of radiation in nearest side lobes vs. angle Θ

The results of the calculation are presented in Fig. 5. As is evident from the figure, the error Δ increases with increase in ε; however, even the maximum error, owing to depolarization in the nearest side lobes, at angles close to $\Theta = 90°$, is not over 15%. At angles Θ_{opt}, the error $\leq$ 10%.

Based on the results of analysis of the errors in determination of the ε and T, owing to the measurement conditions of the experiment and variation in the radiometric apparatus parameters, the following conclusions are drawn.

1. To insure minimum errors in determination of ε and T, the experiment must be carried out, with a radiometer antenna orientation, excluding the regions $\Theta \leq \pm 20°$, $\gamma = 45 \pm 20°$ and $135 \pm 20°$.

2. The greatest partial errors in determination of ε and T result from errors in determination of antenna orientation and errors in measurement of the relative loss in the high-frequency /747 circuits of the vertical and horizontal radiometric apparatus channels.

3. In distinction from an experiment with constant solar-star orientation, polarization measurements of the radio emission of the surface, from aboard a planetary probe in planetocentric orientation, with constant angles of view (θ and γ), permit determination of ε and T along the entire trace of the antenna field of view.

4. In an experiment with planetocentric orientation, the selection of angles of view (θ and γ) is not very critical. To obtain small errors in determination of ε and T, it is sufficient to select θ and γ within: $\theta = 10\text{-}80°$, $\gamma = \pm 10°$.

5. The errors in determination of ε and T depend little on indeterminacy of the degree of depolarization of the radiation in the nearest side lobes of the antenna.

6. With existing apparatus and optimum selection of experimental conditions, the error in determination of ε can be reduced to a value of 10-15%.

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